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Root Flexibility and Untwist Effects on Vibration Characteristics of a Gas Turbine Blade

Jianfu Hou and Bryon J Wicks

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J. Hou and B. Wicks

Air Vehicles Division
Platforms Sciences Laboratory

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ABSTRACT

Blade vibration is generally recognised as one of the most significant causes of high cycle fatigue failure in gas turbine engines. The blade root flexibility often cannot be determined easily in the assessment of blade vibration behaviour and exclusion of this effect may lead to a false prediction of vibration characteristics. This report outlines a study of root flexibility and aerofoil untwist effects on the vibration characteristics of a turbine blade using 3-D finite element analysis, together with laboratory testing. The vibration characteristics of the blade were analysed and the predicted results were correlated with laboratory test results at ambient temperature. The vibration characteristics of the blade assembly during engine operation were then predicted through a pre-stressed modal analysis, including the centrifugal stiffening effect, the temperature effect and the interactions between the blade and disc. The root flexibility effect due to differences in clamping condition was then investigated in detail. Aerofoil untwist effects due to creep were also revealed in this analysis.

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Executive Summary

Turbine blades have been traditionally modelled as a cantilever supported beam in the literature and the blade root flexibility represented by using springs attached to one end of the beam. The analytically indeterminate interactions between the blade and disc firtrees are simplified in order to achieve a linear vibration system. In practice the connection stiffness between the blade and disc firtrees is dependent upon a combination of firtree geometry, materials and the contact condition during engine operation subject to both centrifugal and temperature loads. Hence, the root flexibility of a blade in service may differ substantially from either the fully rigidly fixed condition or the flexible support condition represented by a cantilever beam.

This reports outlines a study of root flexibility and aerofoil untwist effects on the vibration characteristics of a turbine blade using 3-D finite element analysis, together with laboratory testing. It is confirmed with the literature that thermal and centrifugal loads have inherent effects on the vibration characteristics of the blade. For a simple clamped condition, the natural frequency tends to increase with the centrifugal stiffening effect and decrease with the thermal effect, leading to an overall decrease in the natural frequency when the two effects are combined. It is found that the natural frequencies of the blade under in-service loading are higher (up to 13% in the case studied) than the results for the experimental clamped condition. Therefore, the natural frequencies obtained from an experimental test can be only indicative, and could be substantially lower than those experienced in service, and a more sophisticated testing device such a spin rig is required for a more realistic experimental representation. In order to model blade root flexibility in the form of a beam–spring the spring stiffness has to be carefully adjusted for an accurate prediction. Creep during service, including the effects of relaxation of firtree dimensions as well as blade aerofoil untwist, has been shown to increase the natural frequencies to a small degree. This conclusion is supported by both the geometric untwist FE analysis and the experimental results.

Authors

Jianfu Hou
Air Vehicles Division

Jianfu Hou obtained his Ph.D. in Mechanical Engineering from Royal Melbourne Institute of Technology (RMIT). From 1990 to 1991, he was a Visiting Research Fellow working on rotor dynamics topic in the University of Melbourne. In 1992, He joined the Vehicle Safety Research Group at RMIT and worked on injury reduction of car occupants through the design optimisation of airbag and seatbelt restraint systems jointly with GMHA. From 1995 to 1998, he was employed by Worley FEA as a Senior FE Analyst - Dynamics and Fatigue Specialist. Since March 1998, he has been working on propulsion system life management in AVD. At present, he is a senior research scientist and his research interests include engine component analyses, LCF/HCF life predictions, rotor dynamics and blade mistuning, design optimisation and impact simulations.

Bryon J. Wicks
Air Vehicles Division

Bryon Wicks obtained his Ph.D. in Physics from the University of Warwick in the UK. His research background at DSTO has been in studies of the relationship between microstructure and mechanical behaviour of aerospace materials related to the reliability and durability of ADF platforms, and in particular propulsion systems. His interests are in fatigue life prediction and life extension methods. He has the responsibility for the DSTO-AMRL program on Engine Component Life Management.

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1 Introduction

Blade vibration in gas turbine engines has been recognised as one of the most significant causes of high cycle fatigue failure in gas turbine engines. In engineering practice, the blade vibration characteristics are often determined by the blade natural frequencies and the corresponding mode shapes [1,2,3]. A considerable amount of work has already been carried out to determine the natural frequencies and mode shapes of a simplified blade with root flexibility [4~7]. These studies have shown that in general natural frequencies are lowered by the introduction of root flexibility to a rigidly clamped cantilever beam [8]. For an accurate prediction of the natural frequencies of a blade, the boundary conditions set by the blade root fixing have to be taken into account.

Turbine blades have been traditionally modelled as a cantilever supported beam [9,10] and the blade root flexibility represented by using springs attached to one end of the beam [11,12]. In these assumptions the analytically indeterminate interactions between the blade and disc firtrees are simplified in order to achieve a linear vibration system. In practice the connection stiffness between the blade and disc firtrees is dependent upon a combination of firtree geometry, materials and the contact condition during engine operation. Thus turbine blades experience a very complicated contact loading environment including both centrifugal and temperature loads. Hence, the root flexibility of a blade in service may differ substantially from either the fully rigidly fixed condition or the flexible support condition represented by a cantilever beam. Complexities imposed by the blade geometry have to also be considered for an accurate prediction of the root flexibility effect on blade vibration characteristics. Creep in the blades may also occur as blade aerofoil untwist, progressing with the service time, changing the root flexibility and altering the vibration characteristics of the blade. While extensive studies have been carried out for blade vibration analysis, the aerofoil untwist effect on vibration characteristics has not yet been addressed.

In this report, the vibration characteristics of a turbine blade fitted in a military aircraft engine has been analyzed in detail with consideration of the effects of both the blade root interactions and blade untwist, using advanced 3-D finite element (FE) methods and laboratory tests. A 3-D FE model representing a blade and disc assembly was created and analyzed to determine the vibration characteristics of the blade. The blade vibration characteristics were analyzed for various clamping conditions and the predictions were correlated with laboratory test results at ambient temperature. The vibration characteristics of the blade, including the centrifugal and temperature effects and the full interactions at the blade root were determined, and the root flexibility effect was evaluated. The different degrees of root flexibility between blade and disc were quantified for the clamped condition, the in-service condition and the rigidly fixed condition. The effect of aerofoil untwist due to creep on the natural frequencies was investigated together with the effect of varying the blade root flexibility.

2 Blade and Disc Assembly Modelling

Figure 1 shows the blade geometry and the details of the local regions to be analysed. A 3-D finite element model of a blade and a sector of the disc was created, as depicted in Figure 2. Ten-noded tetrahedral elements were used for both the blade and the disc due to the complexity of the geometry, and the most significant geometric features were modelled. The global mesh density was chosen to minimize discretisation errors and a relative finer mesh was designated for the regions of the interest shown in Figure 2.

The tie-bolts and the spacer between the adjacent discs were not modelled and were represented instead by the equivalent loads and boundary conditions. Cyclic symmetry was applied to the model by imposing appropriate displacement constraints. Interactions between the blade firtrees and the disc firtrees were represented using general surface-to-surface contacts without friction. Centrifugal forces were simulated by applying an angular velocity to all elements in the model. A quasi-static gas pressure was also applied over the aerofoil of the blade. A temperature distribution field varying in radial direction, gained from the results of instrumented tests [13], was applied for both the blade and the disc shown in Figure 3. Temperature dependent material data were used to take into account the changes of mechanical properties with temperature. The thermal expansion coefficient, Young's modulus, yield stress and temperature relations are shown in Figures 4 and 5.

3 Basic Vibration Characteristics

3.1 Modal Analysis at Ambient Temperature

The modal analysis simulating the condition of the laboratory tests was carried out in order to determine the accuracy of the model. The major concerns used in this determination were,

a) The model must be reliable; i.e. the difference between model prediction and test results must be acceptable for a specified condition;
b) The model must be robust; i.e. the model must be able to represent the behaviour of the blade for different operating conditions.

The FE model was correlated with a number of laboratory tests at ambient temperature for both free-free and clamped blades (more than 500 modal impact blade tests). In the laboratory clamped tests, the blade firtree regions were clamped on both sides using a clamping jig made by cutting out the disc firtrees. Both faces of each firtree element were in contact with the matching faces of the firtrees of the jig, and the clamping force was set at the maximum consistent with the requirement that there is no plastic deformation of mating surfaces. In the numerical analysis for the clamped condition, the nodes on all of blade firtree outer surfaces were constrained. Table 1 summarises the results of blade vibration modes from tests [14] and their comparison with the FE predictions.

Table 1 Validation results of the FE model

Blade Constraints	No.	Tests (Hz)	FE (Hz)	Type	Diff. (%)
Clamped	1	2043	2101	1 B*	2.8
	2	5000	4954	1 T*	-0.1
Free-free	1	5505	5389	1 B	-2
	2	7080	6902	1 T	-2.5

*B - bending; T- torsional

As shown in Table 1, a close correlation has been achieved between the test results and FE prediction. The reliability of the model is demonstrated by the small difference between of the test results and FE predictions. The robustness is demonstrated by the consistency of the FE prediction with test results for the two representative test conditions of the blades.

Table 2 shows the comparison of the predicted results for blades in the clamped condition with the results for blades in the rigid fixed condition, in which all the nodes (including the inside nodes) within firtree regions were constrained in all the directions. The first and second natural frequencies predicted for blades in the clamped condition are reduced by 8.6% and 3.5% respectively, in comparison with the results for blades in the rigid fixed condition, which is in good agreement with previous findings which have shown that decreasing root flexibility is associated with lower natural frequencies [8].

Table 2. Results comparison between the clamped condition and rigid fixed condition

No.	Clamped (Hz)	Rigid fixing (Hz)	Type	Diff. (%)
1	2101	2281	1 B	8.6
2	4954	5128	1 T	3.5

3.2 Centrifugal Stiffening and Temperature Effects

Centrifugal and temperature loads could not be included in the laboratory test conditions. A centrifugal stiffening effect is caused by the centrifugal force field generated in rotation, such that the apparent blade stiffness increases with the blade rotational speed [15,16]. The effect of higher temperature in the blade is to change the mechanical properties [8]. Both centrifugal and temperature effects were examined in the model by performing a pre-stressed modal analysis for blades in the clamped condition. In a pre-stressed modal analysis, a FE stress analysis is performed first under the applied load, including centrifugal load and thermal load, and then a modal analysis is carried out using the stress and displacement states from the stress analysis as initial conditions. Table 3 summarises the predicted vibration modes for ambient temperature, the effect of stiffening, and the effect of temperature.

Table 3. Vibration mode variations due to centrifugal stiffening and temperature effects

Load	No.	FE (Hz)	Type	Diff.(%)*
Stiffening	1	2168	1 B	3.2
	2	4997	1 T	0.1
Thermal	1	1884	1 B	-10.0
	2	4399	1 T	-11.2
Both	1	1986	1 B	-5.5
	2	4464	1 T	-9.8

*Relative difference from the vibration frequencies at ambient temperature

As indicated in Table 3, the natural frequencies of the blade due to the centrifugal stiffening are increased by 3% in comparison with the experimental condition. However, the natural frequencies decrease by 11% due to the fact that the effect of blade stiffness is decreased at elevated temperatures. As a result, the natural frequencies under the combination of the centrifugal and temperature effects decrease by 5.5 % and 9.8 % for the 1st mode and the 2nd modes respectively. The combined effects lead to lower natural frequencies in comparison with the natural frequencies of the blade in the experimental test condition at ambient temperature. It should be noted that the firtree clamping condition in the laboratory tests does not necessarily represent the real clamping condition of the blade in service. In the latter condition only one face of each firtree for the blade and disc are in contact, and in the experimental clamping condition both faces are in contact. Therefore the predicted temperature and centrifugal stiffening effects on the natural frequencies are only relative and are used for the purpose of comparison.

4 Effect of Root Flexibility on the Vibration Characteristics in the Service Condition

4.1 Blade Firtree Behaviour with Disc Interaction

As discussed in Section 3, the basic vibration characteristics of a blade are described by the natural frequencies and the modal shapes under various clamping conditions. In practice an important concern is the way in which natural frequencies change with the blade root flexibility due to interactions between the blade and disc firtrees under service conditions. A non-linear elastic FE analysis, taking into account the effect of contact stresses, was performed in an attempt to simulate the stress and deformation states of the blade under service conditions. Loads applied include the centrifugal load, the gas pressure loads, the thermal loads and the contact interactions between the blade and the disc firtrees. The change in material properties with temperature is also incorporated. As shown in Figure 6, the maximal principal stresses at each firtree are not evenly distributed, as a result of the offsets between the centre of gravity of the blade and the geometric centre of multiple contact areas from the disc firtree. These clamping conditions are extremely complex and cannot be realistically represented in a vibration test.

4.2 Blade Root Flexibility Effect In-service

A pre-stressed modal analysis was performed to assess the effect of blade root flexibility on the vibration characteristics under service conditions. Table 4 summarises the vibration modes from the analysis and their comparison with the vibration modes under the clamped condition outlined in Section 3.1. The first and second vibration modal shapes are shown in Figure 7.

Table 4. Results from the pre-stressed modal analysis and their comparison with results at the clamped condition in laboratory tests

	In-service (Hz)	Clamped* (Hz)	Type	Variation (%)
Freq	2312	2043	1 B	13.2
	5441	5000	1 T	8.8

* Excluding the temperature and centrifugal stiffening effects

As indicated in Table 4, the 1st and 2nd natural frequencies for the blade under service conditions increase by 13.2% and 8.8% respectively in comparison with the frequencies for the clamped condition in a laboratory test. Factors contributing to the difference include the change in the centrifugal stiffening effect, the temperature effect, and the effective blade root stiffness, which is governed by the different clamping conditions. In a clamped condition, both faces of each firtree element were fixed such that the temperature load and the centrifugal load are shared between the two fixed faces. Under service conditions, only the upper face of each firtree element is in contact with the matching face of the disc firtree and consequently the loads are transferred through the single face to the disc. The form of interaction between the blade firtrees and the disc firtrees should be carefully considered in any analysis of the blade vibration characteristics.

5 Effects of Creep on Vibration Characteristics

The blade geometry during service may progressively change due to creep, leading to blade aerofoil untwist relative to the stake axis and blade growth in the radial direction. As a result, the natural frequencies of the blade may alter with the length of time the blade is in service [17].

5.1 Blade Aerofoil Untwist Effect

The blade aerofoil untwist can be investigated [14] experimentally by untwisting the blade shroud and aerofoil relative to the side edge of the shroud and then by then carrying out a modal test to determine the natural frequencies. Alternatively this can be achieved using FE analysis by rotating the geometry of the blade shroud and airfoil around the stacking axis. Both the experimental and analytical methods represent purely geometric untwist, they do not take into account the effect of centrifugal loads, thermal loads or contact stresses.

A modal analysis was performed using the FE model of the untwisted geometry for both the clamped condition and the free-free condition. The frequencies for before and after untwist are given in Table 5 for a untwist of 2.5 degrees relative to its original orientation. This degree of untwist represents a typical untwist in service.

Table 5. FE geometric untwist results and variations relative to original values before untwist

Blade Constraint	Clamped (Hz)	Variation (%)	Free	Variation (%)
Frequency	2107	0.3	5454	1.1
	4987	-0.7	6802	-1.4

As Table 5 shows, the variations in natural frequency due to the geometric untwist are very small (1.4% maximum) for both the clamped condition and the free-free condition. This indicates that the natural frequencies will change very little with the service time if the only effect considered is geometric untwist. However, Table 5 does not include the creep growth, centrifugal load, temperatures or root stiffness, and a more rigorous modal analysis in the pre-creep condition needs to be carried out for a more realistic estimate of the untwist effects.

5.2 Blade Aerofoil Untwist Combined with Other Creep Effects

Under service conditions, the creep occurs progressively with the service time, subject to the centrifugal load and thermal expansion. This process can be simulated by using a creep analysis with two steps: (a) a non-linear FE stress analysis to achieve the quasi-static equilibrium under the applied load and (b) a creep analysis for a specified service time under the applied load. Because extensive creep data is not available for the material for the blade being studied, a conservative estimate may be derived by using typical creep data for a similar material which is more creep resistant for the same stress and temperature combination [18]. A creep analysis with a service time of 3000 hours was performed to achieve the stress and displacement state required for the subsequent modal analysis. Figure 8 shows the maximum principal stress plot of the blade at the firtrees, indicating that the clamping condition changes slightly at the firtree regions, caused by stress relaxation due to creep. The calculated untwist after 3000 hours is 3 degrees with a radial growth of 0.3 % of blade length.

Following the creep analysis, a modal analysis was performed to determine the natural frequencies of the blade after the 3000 hours service. The calculated blade natural frequencies after creep and the comparison of the results at the service condition are summarised in Table 6.

Table 6. Combined effects of creep

Blade Constraint	Original (Hz)	Creep affected (Hz)	Type	Variation (%)
Frequency	2312	2418	1 B	4.6
	5441	5568	1 T	2.3

The results in Table 6 show that the blade natural frequencies increase slightly with the progress of blade aerofoil untwist accompanied by other creep effects. This is mainly due to the modification of the clamping condition between the disc and blade firtrees with increasing service time, resulting in better matching contacts between firtrees due to creep deformation.

6 Conclusions

The effect of blade root flexibility for a turbine blade has been investigated using advanced FE techniques, including a pre-stressed and pre-creeped modal analysis for the blade. In order to make reliable predictions for various loading conditions, the FE model was validated with experimental test results and close agreement was achieved for all the available test cases.

Thermal and centrifugal loads have inherent effects on the vibration characteristics of the blade. For a simple clamped condition, the natural frequency tends to increase with the centrifugal stiffening effect and decrease with the thermal effect, leading to an overall decrease in the natural frequency when the two effects are combined.

Simulation of the blade under in-service loading has shown that the blade natural frequencies are higher (up to 13% in the case studied) than the results for the experimental clamped condition. Therefore, the natural frequencies obtained from an experimental test can be only indicative, and could be substantially lower than those experienced in service, and a more sophisticated testing device such a spin rig is required for a more realistic experimental representation. In order to model blade root flexibility in the form of a beam-spring the spring stiffness has to be carefully adjusted for an accurate prediction.

Creep during service, including the effects of relaxation of firtree dimensions as well as blade untwist, has been shown to increase the natural frequencies to a small degree. This conclusion is supported by both the geometric untwist FE analysis and the experimental results.

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Appendix A:

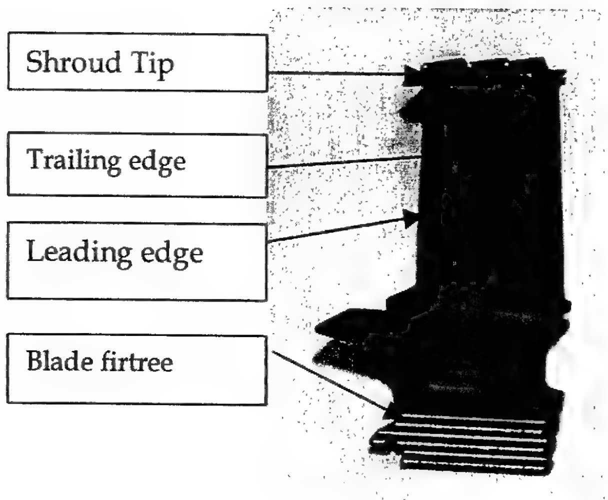


Figure 1 Blade geometry and details

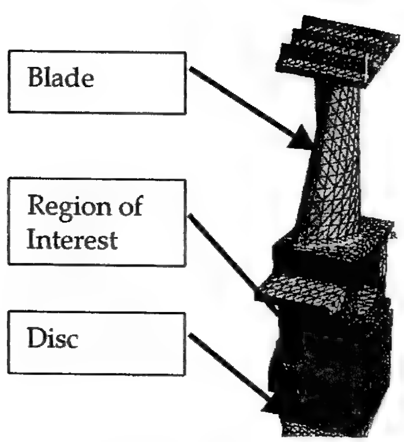


Figure 2 3-D finite element model of the blade and disc assembly

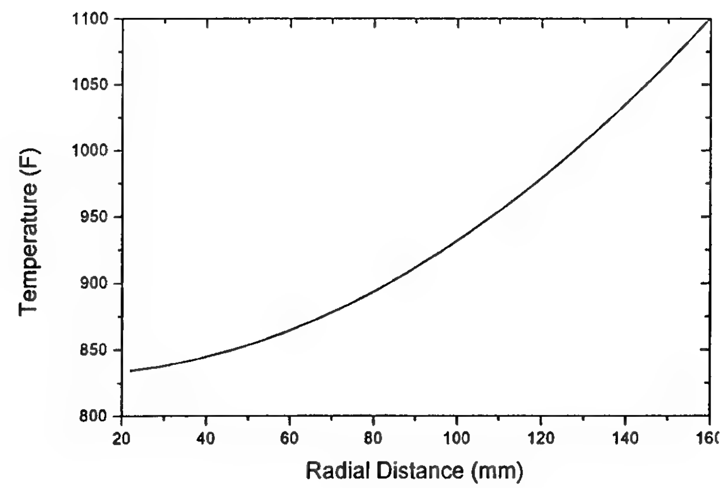


Figure 3 Temperature distribution

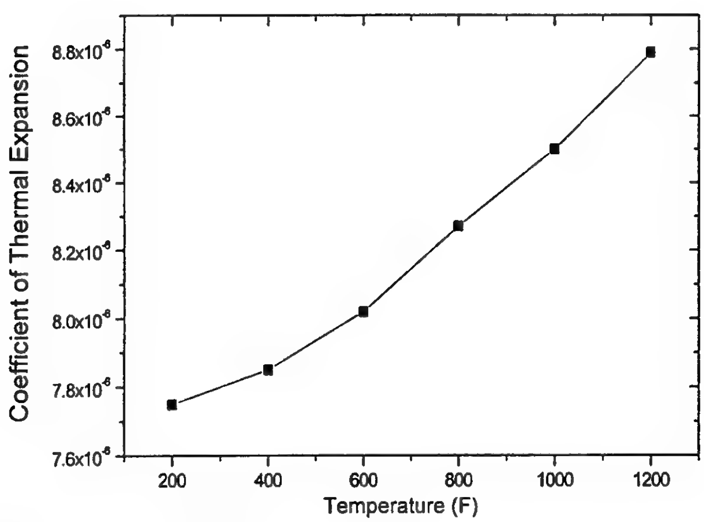


Figure 4 Coefficient of thermal expansion

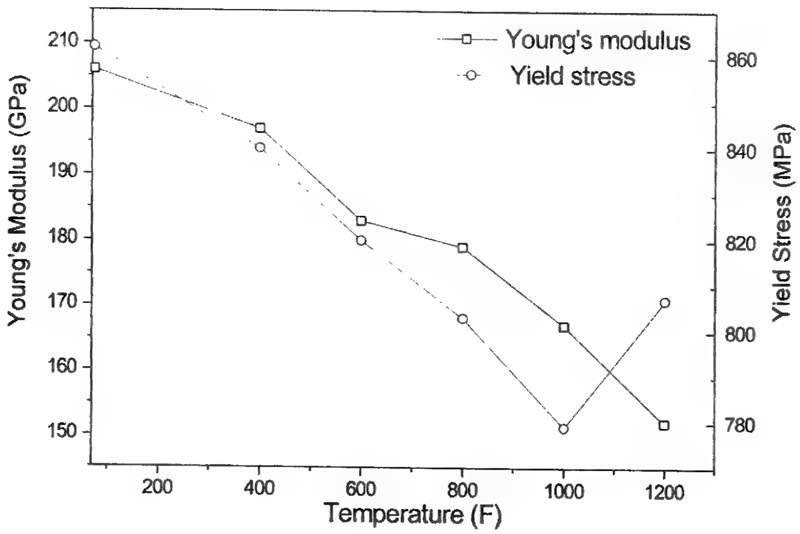


Figure 5 Material Properties

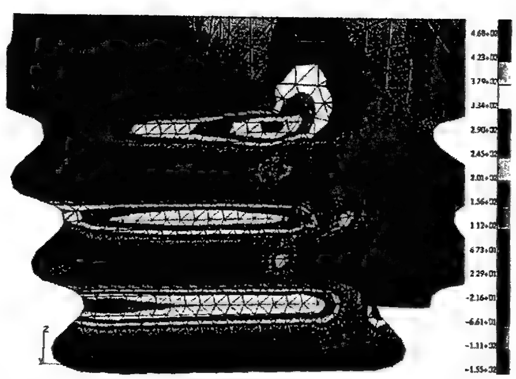
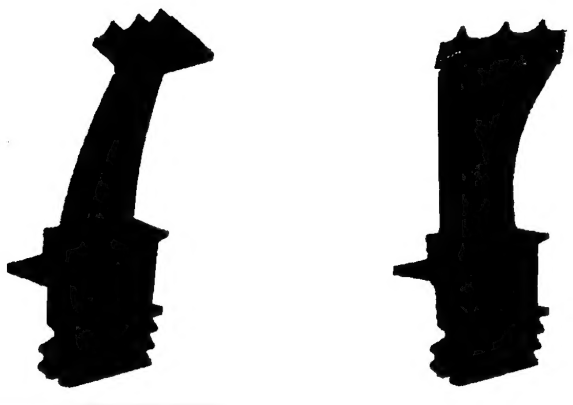


Figure 6 Stress distribution at firtrees under normal engine operating condition



a) 1B mode b) 1T mode

Figure 7 Vibration modes of the blade at in-service condition

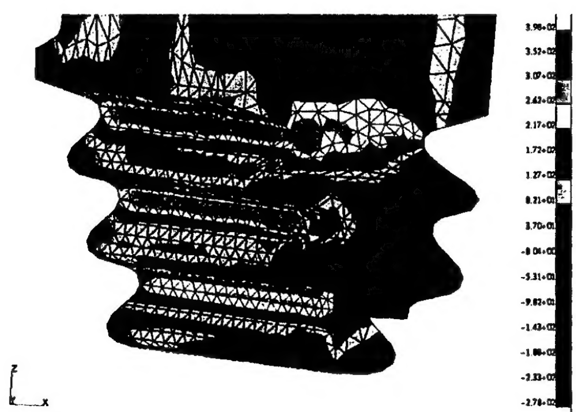


Figure 8 Stress distribution at firtrees under normal engine operating condition after 3000 hours creep

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4. AUTHOR(S) Jianfu Hou and Bryon J Wicks			5. CORPORATE AUTHOR Platforms Sciences Laboratory 506 Lorimer St Fishermans Bend Vic 3207 Australia		
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19. ABSTRACT

Blade vibration is generally recognised as one of the most significant causes of high cycle fatigue failure in gas turbine engines. The blade root flexibility often cannot be determined easily in the assessment of blade vibration behaviour and exclusion of this effect may lead to a false prediction of vibration characteristics. This report outlines a study of root flexibility and untwist effects on the vibration characteristics of a turbine blade using 3-D finite element analysis, together with laboratory testing. The vibration characteristics of the blade were analysed and the predicted results were correlated with laboratory test results at ambient temperature. The vibration characteristics of the blade assembly during engine operation were then predicted through a pre-stressed modal analysis, including the centrifugal stiffening effect, the temperature effect and the interactions between the blade and disc. The root flexibility effect due to differences in clamping condition was then investigated in detail. Untwist effects due to creep were also revealed in this analysis.